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A SUMMARY OF STUDIES PERFORMED ON EXPERIMENTAL ACCELERATED COOLED/DIRECT QUENCHED PLATE STEELS FOR ARMOR APPLICATIONS AS PART OF THE TITLE III PROGRAM OF THE DEFENSE PRODUCTION ACT

JUDITH L. BHANSALI
MATERIALS PRODUCIBILITY BRANCH

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ABSTRACT

In an effort to minimize the welding preheat required during armored vehicle manufacture, low-carbon accelerated cooled/direct quenched (AC/DQ) steels are being studied as possible alternatives to the currently specified and used rolled homogeneous armor (RHA).

Low-C steels produced by Nippon Steel Corporation and Kawasaki Steel Company (both of Japan) using AC/DQ technology have been compared, on a limited basis, to the MIL-A-12560 specification and to typical RHA provided to the U.S. Army by one supplier. Japanese material was evaluated because the AC/DQ technology is used in Japanese steel mills. If the technology proves to be useful, it could be transferred to U.S. steel mills under the Title III program.

Low-C steels produced by Bethlehem Steel Corporation (in the U.S.A.), using a laboratory AC/DQ mill, were also compared to the MIL-A-12560 specification and to RHA which is supplied to the U.S. Army by one supplier.

None of the steel samples that were tested performed as well as does the RHA which is currently being supplied to the Army. Overall, the experimental steels did not perform as well as RHA, which is currently being supplied to the Army. It is difficult, on the basis of the limited sample used in this study, to assess the effects of lower carbon content and of AC/DQ processing.

CONTENTS

BACKGROUND

In May, 1986, the Naval Sea Systems Command initiated a Defense Production Act (DPA) Title III Purchase Commitment Program to develop a domestic capacity for producing accelerated cooled/direct quenched (AC/DQ) processed steels. Steel plates produced using this thermomechanical process would be used for Naval vessel and armored vehicle construction. This summary is drawn from correspondences between the participants, various meetings, the Request for Proposals written for this program, and the limited studies performed on the sample steels. The steels produced using AC/DQ would replace some existing steels in Navy and Army applications. The reason for developing the domestic capacity for producing AC/DQ steels is to reduce the use of strategic alloy materials, to save energy during manufacture, thus reducing the cost of DoD steel plate. The DPA Title III program provides incentive through purchase commitments of the material, not by paying directly for the establishment of AC/DQ facilities.

This form of thermomechanical processing has been widely introduced into the Japanese steel industry since 1981. It employs an array of computer-controlled water cooling fixtures to closely control the cooling rate of hot-rolled steel plate. Because it is quenched off the hot mill, the steel does not require energy and labor intensive homogenizing. The resultant steel has improved strength and toughness which allows for reducing the alloy and carbon contents while still meeting property requirements. The reduced carbon content enhances the weldability, therefore, this processing has reduced strategic mineral requirements for alloying ship-grade steels, reduced production-related energy requirements, improved weldability, and increased strength and toughness for the Japanese steel industry.

The use of accelerated cooling by the domestic steel industry would provide the same savings and benefits as experienced by the Japanese steel industry, namely savings of strategic materials, energy and labor costs, and enhanced properties. The AC/DQ steel plate would be used in the construction of all classes of Naval vessels, tanks and other armored vehicles, missile carriers, and for fixed construction, and would benefit the Navy, Marine Corps, Army, and Air Force.

As the DoD demand for high strength, tough, weldable steel plate has increased, the domestic steel industry has not kept pace with modern plate production technology. The high strength steel plate is produced domestically using older steelmaking concepts which utilize large amounts of strategic alloying elements (chromium, nickel, molybdenum) and labor and energy intensive heat treatment operations to obtain the unique properties required for military applications. There are currently only three suppliers which can meet the requirements of HY-80/100 plate for Naval construction. Furthermore, the welding of these steels requires preheating and close interpass temperature control during vehicle construction to prevent weld cracking, resulting in increased energy costs and reduced production efficiency.

INTRODUCTION

This Title III program is composed of three phases: qualification of AC/DQ produced steels, installation of one AC/DQ facility, and establishment of a second AC/DQ facility. The first phase includes a competitive award for a purchase commitment to qualify four grades of steel and incorporate these steels into vehicle structures. To assure that the alloys qualified are compatible with existing domestic melting and molten metal processing plant capabilities, all melting, alloying, molten metal treatment, and processing to the slab stage shall be

performed in domestic plants. Because the AC/DQ technology is foreign-based, plate rolling and AC/DQ treatment may be performed in foreign mills.

The second phase will be competitively awarded to one supplier for installation of an AC/DQ facility, first article inspection of the alloy grades, facility certification, and purchase commitment for production quantities of AC/DQ plate.

The third phase will be the competitive award to a second supplier for installation of an AC/DQ facility, first article inspection of the alloy grades, facility certification, and the purchase commitment for production quantities of AC/DQ plate.

As of this writing, August, 1989, the source selection for Phase I of this program is in progress; the Title III office expects to award a contract(s) during the fall of 1989. There have been some preliminary studies on different compositions of steels manufactured using AC/DQ techniques in conjunction with this program. These studies are summarized in three of U.S. Army Materials Technology Laboratory (MTL) Letter Reports (see Appendices A, B, and C).

Since these reports are included herein, the details of procedure will not be discussed. Instead, the following discussion of analyses of the various experimental materials is provided.

DISCUSSION

The Japanese steels contained very low carbon levels compared to the rolled homogeneous armor (RHA) currently supplied per MIL-A-12560 specification (typical RHA).

The Nippon Steel Corporation (NSC) steel had less Mn and B, but more Ni and Cr than typical RHA, as reported in Appendix A. It had similar mechanical properties and only slightly lower hardness. However, the toughness of the NSC steel was much greater than that of typical RHA. This NSC material performed poorly against 20 mm AP, TM602, and .50 cal. AP, M2 ballistic projectiles.

The material from Kawasaki Steel Company (KSC) contained more Mn and Mo, but less Ni and Cr than does typical RHA, as found in Appendix B. The mechanical properties were about 10% lower than those of typical RHA, but, as for the NSC material, the toughness was much greater than that of typical RHA. The hardness of the KSC steel was similar to that of typical RHA (37 HRC). The ballistic performance met the minimum specified by MIL-A-12560, but did not measure up to that of typical RHA. The Kawasaki plate exhibited a depth of penetration by the 91% W, L/D=10 long rod penetrator similar to that of typical RHA.

The steels from Bethlehem Steel Corporation (BSC) had lower carbon than RHA, but greater than the Japanese steels and were similar to the typical RHA except for additions of either Cb or V, as shown in Appendix C. The surface hardness for both materials just met the minimum specified in MIL-A-12560. The toughness was slightly better than that of typical RHA. There are no mechanical property data to report for these materials. Both of the BSC experimental steels did not meet the minimum ballistic performance specified in MIL-A-12560 for .50 cal. AP, M2 threat.

SUMMARY

As part of a Defense Production Act Title III Purchase Commitment Program to develop a domestic capacity for producing accelerated cooled/direct quenched steels, the U.S. Army Materials Technology Laboratory has done some preliminary studies on AC/DQ steels. The Title III program involves determining the capability of producing AC/DQ steels for armored vehicle construction for the Navy and the Army, and the subsequent installation of AC/DQ capacity in the United States. Currently, the process is used only in foreign-based steel mills in Europe and Japan.

Accelerated cooled/direct quenched processing of steel plates involves the use of water cooling after the plates have been hot-rolled by controlled rolling practices to the final thicknesses and planar dimensions required. This technology was developed in the early 1980s and is in use in Japan and Europe. In applications for shipbuilding, this technology has resulted in steels with lower carbon and lower carbon-equivalent levels, which are more weldable. Savings are anticipated in the areas of critical alloying elements, steel processing, and vehicle fabrication.

Brief studies have been done on samples of AC/DQ steels from Nippon Steel Corporation and Kawasaki Steel Company to obtain an idea of the materials which can be produced in existing mills, and on samples from Bethlehem Steel Corporation. Since one intention of this program is to improve the weldability through the reduction of carbon contents, the materials studied by MTL have lower carbon levels than that currently specified for rolled homogeneous armor. The steels from Japanese steel mills had 0.11% carbon; the material from BSC contained about 0.17% carbon. The AC/DQ processed steels from all three sources did not perform as well as RHA in standard ballistic tests even through the hardnesses were not excessively different from RHA. The steels from NSC *and* KSC were much tougher than currently supplied RHA, as measured using the Charpy V-notch test.

The Title III program is scheduled to award a contract(s) during the fall of 1989 for the first phase of the program, the qualification of steels produced using this technology for armored vehicle construction. MTL will receive samples of the steels produced as possible substitutes for RHA as part of this phase for testing and characterization. Also, the point-of-contact (POC) for this program at MTL will be a member of the technical evaluation team with representatives from the Navy.

APPENDIX A.

LETTER REPORT

A BRIEF STUDY OF LOW-CARBON ACCELERATED COOLED/DIRECT QUENCHED STEEL FROM NIPPON STEEL CORPORATION

JUDITH L. BHANSALI
Materials Producibility Branch
Materials Exploitation Division

AUGUST 1989

U. S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

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ILLUSTRATIONS

ABSTRACT

In an effort to minimize the welding preheat required during armored vehicle manufacture, low-carbon accelerated cooled/direct quenched (AC/DQ) steels are being studied as possible alternatives to the currently specified and used rolled homogeneous armor (RHA).

A low-C steel produced by Nippon Steel Corporation (Japan) using AC/DQ processing was compared to MIL-A-12560 specifications and to typical properties of Mn-Mo-B RHA plate. Japanese material was evaluated because the AC/DQ technology is being used by Japanese steel mills, and if the technology proves to be useful, it could be transferred to U.S. steel mills using Title III funds. The AC/DQ processed steel contains only 0.11% carbon and is alloyed with 1.04% nickel and 0.56% chromium.

The Nippon Steel Corporation (NSC) material has tensile properties similar to those of typical RHA. The AC/DQ material has slightly lower surface hardness but much greater toughness than MIL-A-12560 specifies or than typical RHA exhibits. However, in spite of the greater toughness, the material has poor ballistic properties, not quite meeting the minimum specification and not performing as well as the typical RHA material.

INTRODUCTION

As part of a larger study of low-carbon accelerated cooled/direct quenched steels for armor materials, physical properties and ballistic data were obtained on some samples of 1-inch thick low-carbon rolled steel plate from Nippon Steel Corporation of Japan. The impetus for lowering the carbon content in rolled homogeneous armor is the elimination or minimization of welding preheat during armored vehicle fabrication.

PROCEDURE

The chemistry of samples of low-carbon rolled steel plate, provided by NSC, and properties determined at the Materials Technology Laboratory (MTL) were compared to MIL-A-12560 specifications and to typical RHA steel. Tensile properties were measured on a 20K Instron Electromechanical Test machine at room temperature and humidity (68 F/55% RH), a 1"-10% extensometer was plotted through a Houston x-y recorder for strain, and load/time curves were generated. Through-thickness hardness values were measured, and -40 F Charpy V-notch impact tests were done on L-T and T-L samples. The CVN tests were done using the Satoc 240 ft.-lb Impact Machine with instrumented tup. The ballistic V_{50} was measured for 20 mm AP TM602- and .50 caliber AP M2-type threats at 0 degree obliquity and compared to MIL-A-12560. Micrographs were made of the grain structure.

RESULTS AND DISCUSSION

The chemistry of the 1" Nippon plates compared to typical 1" RHA shows less than one-half the carbon content and greater nickel and chromium contents. The Japanese steel also contains some vanadium and copper.

Table 1. CHEMISTRY OF LOW-C NSC STEEL VS. TYPICAL RHA

Element	% NSC	% RHA
C	0.11	0.25
Mn	0.91	1.59
Mo	0.45	0.53
B	0.0016	0.0019
Ni	1.04	—
Cr	0.56	—
Si	0.25	0.26
S	0.001	0.004
P	0.003	0.020
V	0.05	—
Cu	0.25	—

Mechanical properties were obtained. It was noted that the longitudinal tensile specimens had an elliptical cross section after failure and diameters were averaged to obtain percent reduction of area.

Table 2. MECHANICAL PROPERTIES OF LOW-C NSC STEEL VS. 1-INCH TYPICAL RHA

Source	Orientation	0.2% YS ksi	UTS ksi	% El	% RA
Nippon	Longitudinal	141.1	146.1	18.8	69.5
	Transverse	149.6	153.2	18.9	69.3
Typical RHA	Longitudinal	145.4	154.3	18.3	NA
	Transverse	145.9	154.3	15.8	NA

Through-thickness hardness was measured on the 1"-thick Nippon steel. Surface hardness was 33.6 HRC. The through-thickness hardness, measured at 1/10th-inch intervals and shown in Figure 1, varied from 34.6 to 35.2 HRC, being fairly uniform throughout. MIL-A-12560 specifies a surface hardness in the range of 34.3 to 40.5 HRC for RHA 0.750 to 1.249 inches thick. The through-thickness hardness of typical RHA varies 1 to 2 HRC points.

Charpy V-notch impact energy values for the NSC steel were obtained for comparison to typical RHA and to the specification.

Table 3. TOUGHNESS OF 1-INCH LOW-C NSC STEEL, CVN AT -40 F

Source		CVN, -40 F ft.-lb
Nippon	TL	103.0
	LT	91.6
Typical RHA	TL	18-31
	LT	21-31
MIL-A-12560*		23.5 minimum

*At HRC 33.6

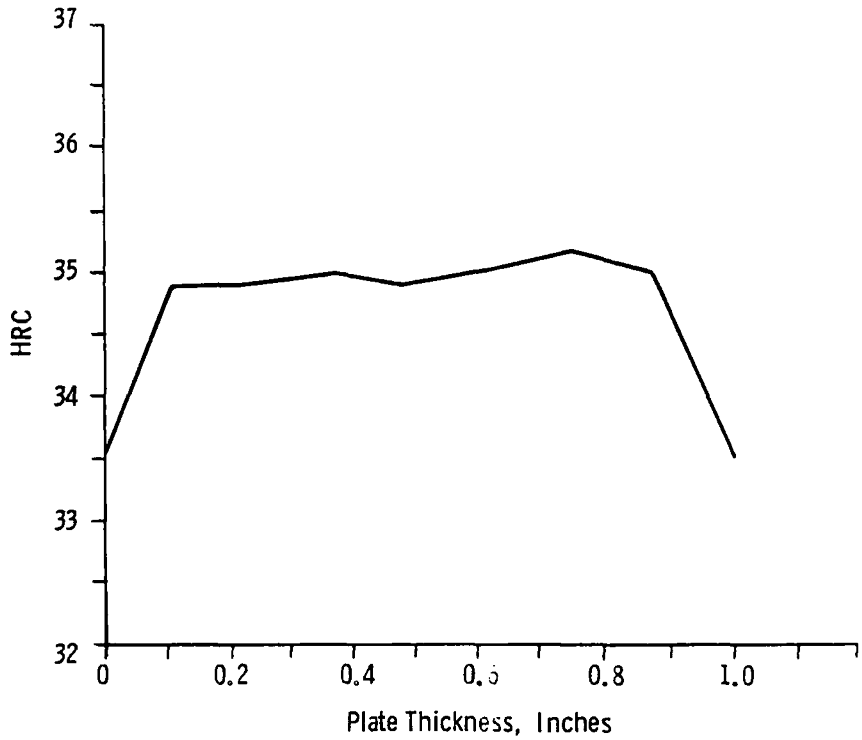

Figure 1. Through-thickness hardness of low-C NSC steel.

The ballistic V_{50} of the NSC steel was slightly lower than the minimum specified for MIL-A-12560 using 20 mm AP TM602- and .50 cal. AP, M2-type threats, as shown in Table 4. There was no apparent tendency to spall with either projectile.

Table 4. BALLISTIC PERFORMANCE OF 1-INCH LOW-C NSC STEEL

Projectile	V_{50}, fps NSC	V_{50}, fps MIL-A-12560
20 mm AP, TM602	1853 t=1.015"	1875[1]
.50 cal. AP, M2	2690 t=1.0165"	2702[2]

1. Mascianica, F. S., "Ballistic Technology of Lightweight Armor - 1976 (U).", Army Materials and Mechanics Research Center, AMMRC TR 76-15, May 1976 (Confidential Report)
2. 1" to 1.02" thick. Note: RHA exceeds the minimum MIL-A-12560 V_{50} requirement by an average 87 fps.

SUMMARY AND CONCLUSIONS

Low-carbon, accelerated cooled/direct quenched (AC/DQ) type rolled homogeneous armor (RHA) material from Nippon Steel Corporation (NSC) of Japan was evaluated as a part of a larger study to low-carbon AC/DQ steels for armor materials.

1. The NSC steel contains less manganese and boron and more nickel and chromium than typical Mn-Mo-B RHA per MIL-A-12560.

2. The NSC steel has tensile strength and elongation similar to typical RHA material.

3. The surface hardness of the NSC material was slightly lower than specified in MIL-A-12560 (33.6 vs. 34.3 HRC). Through-thickness hardness was within the surface specification and did not vary excessively.

4. Toughness measured by CVN impact testing was much greater than specified in MIL-A-12560 or than typical RHA.

5. The NSC plate performed poorly in ballistic testing. For 20 mm AP, TM602 and .50 cal. AP, M2 threats, the V_{50} measured were slightly lower than that shown in the Mascianica handbook or than the minimum specified by MIL-A-12560, respectively, and were much lower than for typical RHA.

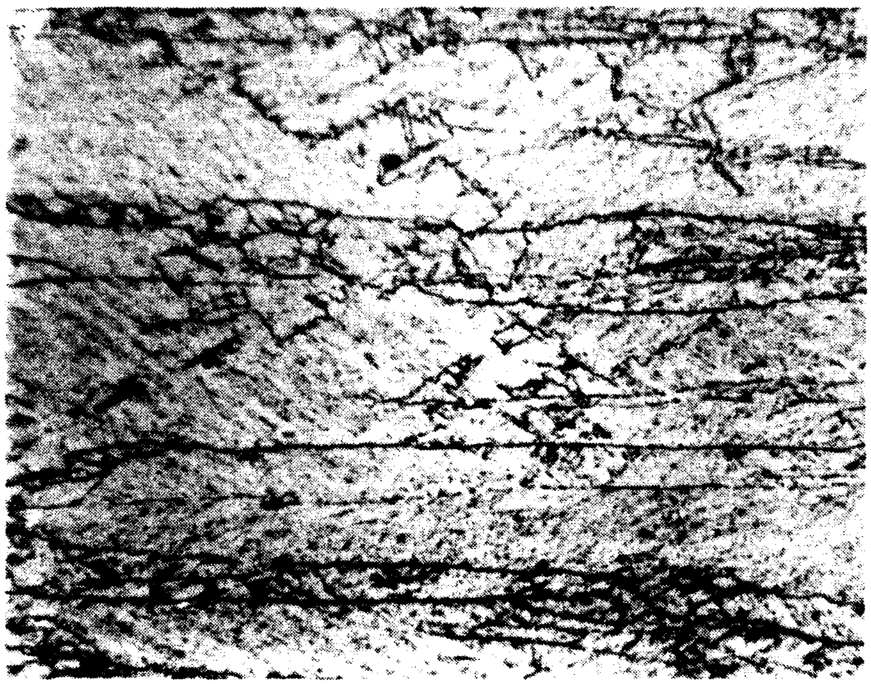

Figure 2. Microstructure of 1-inch Nippon plate, 800X, longitudinal.

ACKNOWLEDGMENT

The author wishes to thank Mr. Arthur Ayvazian for sharing his vast knowledge of the properties of Rolled Homogeneous Armor steels in use by the U.S. Army.

APPENDIX B.

LETTER REPORT

A BRIEF STUDY OF LOW-CARBON ACCELERATED COOLED/DIRECT QUENCHED STEEL FROM KAWASAKI STEEL COMPANY

JUDITH L. BHANSALI
Materials Producibility Branch
Materials Exploitation Division

AUGUST 1989

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

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LIST OF ILLUSTRATIONS

ABSTRACT

Low-carbon, accelerated cooled/direct quenched (AC/DQ) steels are being studied as possible alternatives to the currently specified and used rolled homogeneous armor in an effort to minimize the welding costs during armored vehicle construction. Because the AC/DQ technology is not used in this country, but is used in Japan, this preliminary study is of a Japanese steel produced using this technology. The steel studied contained only 0.11% C and had 1.55% Ni and 0.55% Cr. The mechanical properties of the KSC steel were about 10% lower than those of 2-inch RHA, surface hardness was within that specified for RHA, but through-thickness hardness varied more in the KSC steel than it does in RHA. The steel exhibited a gradient microstructure with smaller grains in the center of the plate. The toughness values from CVN impact tests were much greater than for RHA. The ballistic behavior was marginal, meeting the minimum specified, but was not as high as that of RHA.

INTRODUCTION

As part of a larger study of low-carbon (low-C) accelerated cooled/direct quenched (AC/DQ) steels for rolled homogeneous armor (RHA), some samples of 2-inch-thick steel plates manufactured by Kawasaki Steel Company (Japan) were compared to typical 2-inch-thick RHA and to MIL-A-12560 specifications.

PROCEDURE

Chemistry of the steel, supplied by Kawasaki Steel Company (KSC), was compared to an average composition supplied by one producer of 2-inch RHA. Mechanical properties, supplied by KSC, were compared to those typical of 2-inch RHA. Surface and through-thickness hardness measurements were made. Micrographs were taken of the grain structure.

Charpy V-notch (CVN) impact specimens were tested using a 240 ft.-lb Weidemann impact test machine with an instrumented tup and a Nicolet oscilloscope. Energy absorbed at fracture was compared to the MIL-A-12560 specifications and to typical RHA.

The V_{50} ballistic limit was measured using the 20 mm AP, M602 projectile at 0 degrees obliquity for comparison to MIL-A-12560. Ballistic penetration was determined to compare to 4-inch-thick RHA. In this instance, the 2-inch-thick plates were surface-ground to flat surfaces and clamped securely together. Then the composite was fired at with the standard 91% W, L/D=10 quarterscale rod. Two shots were taken.

RESULTS AND DISCUSSION

The chemistry supplied by Kawasaki is shown in Table 1, compared to an average composition of 2-inch RHA supplied by one domestic producer.

Table 1. CHEMICAL COMPOSITION, WEIGHT PERCENT, OF 2-INCH LOW-C KSC STEEL VS. RHA

Element	Kawasaki	RHA
C	0.11	0.28
Mn	0.86	0.28
Mo	0.55	0.25
B	—	—
Ni	1.55	2.20
Cr	0.55	1.40
Si	0.10	0.27
S	0.001	0.002
P	0.003	0.012
V	0.76	—
Al	0.58	0.040

Mechanical properties reported by Kawasaki, shown in Table 2, are about 10% lower than those properties which are typical for 2-inch RHA. However, the % elongation is 25% greater for the KSC steel.

TABLE 2. MECHANICAL PROPERTIES OF 2-INCH LOW-C KSC STEEL VS. RHA

Source	Orientation	0.2% YS ksi	UTS ksi	%El
Kawasaki	Transverse	131	138	20
RHA	Transverse	145	154	16

Surface and through-thickness hardness measurements revealed surface hardness of 37 HRC and center hardness as low as 33.5 HRC, as shown in Figure 1. The hardness of typical RHA varies 1 to 2 HRC points through the thickness in steel thicknesses up to 2 inches.

Photomicrographs of the Kawasaki material, shown in Figure 2, show a gradient in microstructure with depth into the plate.

The toughness of the Kawasaki steel was measured by Charpy V-notch testing at -40 F. The Charpy values, shown in Table 3, are very high compared to that specified by MIL-A-12560 or exhibited by typical 2-inch RHA. The specimens did not break completely apart but remained hinged together, as shown in Figure 3.

Table 3. TOUGHNESS OF 2-INCH LOW-C KSC STEEL, SVN AT -40 F

Source		CVN, -40 F ft.-lb
Kawasaki	TL	119.5
	LT	67.2
RHA#	TL	25
	LT	25
MIL-A-12560*		21.2

#Brinell hardness 331 (HRC 35.4)
*Brinell hardness 344 (HRC 37)

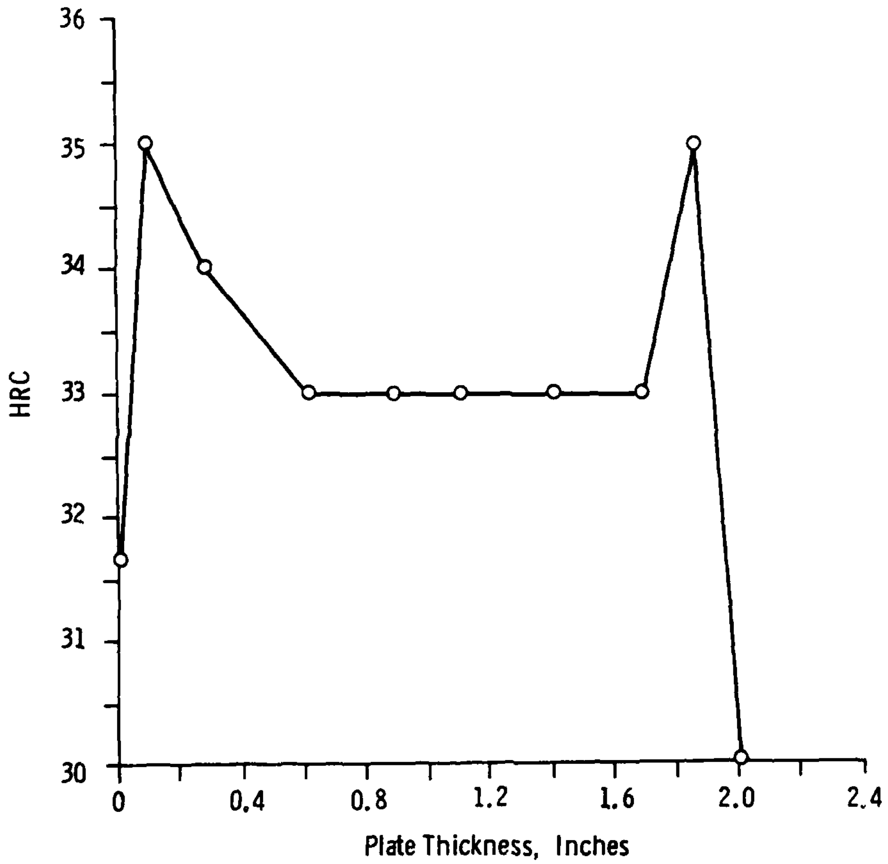


Figure 1. Through-thickness hardness of low-C KSC steel.

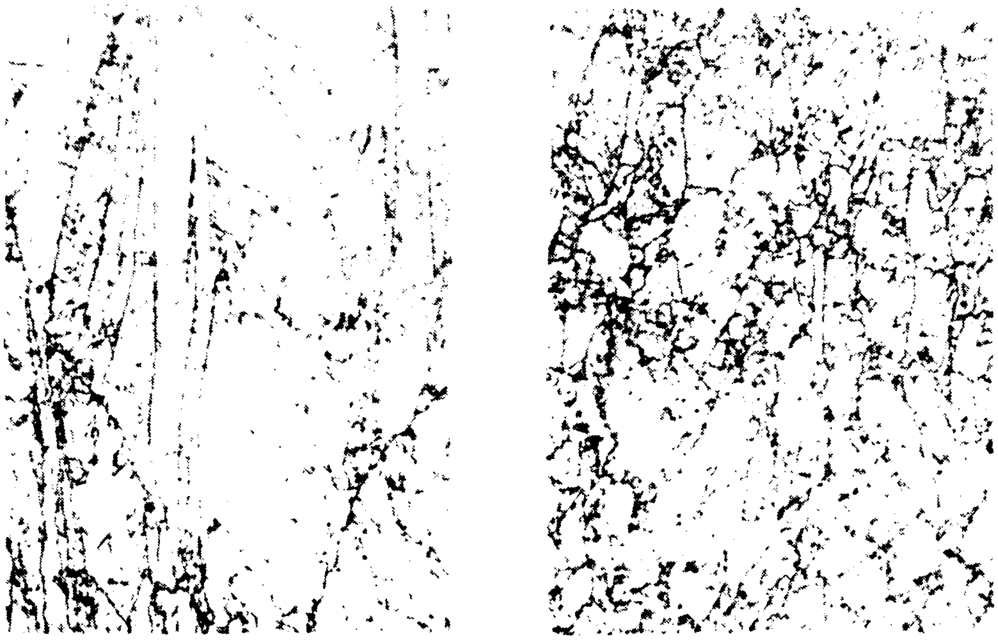
The 2-inch plates were tested against 20 mm AP-M602 projectiles to determine the V_{50}. The average V_{50} from twelve shots each on 3 different test plates was 2878 fps. Table 4 compares the Kawasaki plate to the MIL-A-12560 minimum specification of 2862 fps at this thickness. Typical 2-inch RHA exceeds the minimum by an average 84 fps.

The Kawasaki plate performed the same as 4-inch monolithic RHA in the depth of penetration test using the 91% W, L/D=10 quarterscale rod penetrator, even though the hardness of the KSC plate was near 36 HRC, and the RHA tends to be about 27 HRC.

Table 4. BALLISTIC PERFORMANCE OF 2-INCH LOW-C KSC STEEL

Projectile	V_{50}, fps KSC	V_{50}, fps MIL-A-12560
20 mm AP, M602 t=2.010"	2878	2862*

*Typical 2-inch RHA exceeds the minimum by an average 84 fps



(a) (b)

Figure 2. Microstructure of 2-inch Kawasaki plate. (a) Near the surface (b) Near the center. 500X.

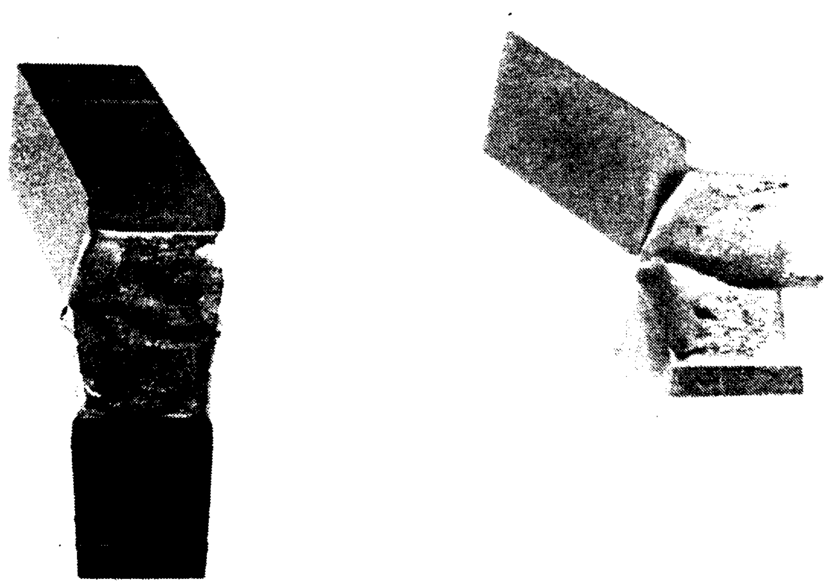


Figure 3. Charpy specimens of Kawasaki steel showing the unbroken hinge.

CONCLUSIONS

A low-C, accelerated cooled/direct quenched steel from Kawasaki Steel Company of Japan was evaluated as part of a larger study of low-carbon AC/DQ steels for armor material.

1. The 2-inch-thick KSC steel contains more manganese and molybdenum and less nickel and chromium than the average 2-inch RHA from one domestic producer.

2. The 0.2% offset yield and ultimate tensile strengths of the Kawasaki steel are about 10% lower than those of typical RHA, but the % elongation of the KSC steel is 25% greater than that of RHA.

3. Surface hardness of the KSC steel was well within the range specified by MIL-A-12560. The through-thickness hardness varied more in the KSC steel than it does in typical RHA.

4. Toughness measured by CVN impact testing was much greater in the KSC steel than that specified in MIL-A-12560 or than that exhibited by typical RHA.

5. The KSC plate had slightly higher V_{50} than the minimum specified by MIL-A-12560 in ballistic tests, but did not perform quite as well as does the typical 2-inch RHA.

6. The Kawasaki plate was equivalent to RHA in the depth of penetration test using the 91% W, L/D=10 long rod penetrator.

ACKNOWLEDGMENT

The author wishes to thank Mr. Arthur Ayvazian for sharing his vast knowledge of the properties of Rolled Homogeneous Armor steels in use for U.S. Army applications, and Mr. Charles Hickey for his ready advice.

APPENDIX C.

LETTER REPORT

A BRIEF STUDY OF LOW-CARBON ACCELERATED COOLED/DIRECT QUENCHED STEEL COMPOSITIONS FROM BETHLEHEM STEEL CORPORATION

JUDITH L. BHANSALI
Materials Producibility Branch
Materials Exploitation Division

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U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

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ILLUSTRATIONS

ABSTRACT

As part of a larger study of low-carbon accelerated cooled/direct quenched (AC/DQ) steels for applications in armored vehicles, two experimental direct quenched steel compositions were studied. These alloys, produced by Bethlehem Steel Corporation (BSC), contained less carbon and manganese than does Rolled Homogeneous Armor (RHA) and had additions of either columbium or vanadium. surface hardness of the 1-inch-thick plates was on the low side of the specified range. The toughness values, measured using CVN tests, were good compared to RHA. The ballistics were poor, below the minimum specified at the thickness tested.

INTRODUCTION

As part of a larger study of low-carbon (low-C) accelerated cooled/direct quenched (AC/DQ) steel for armor applications, two experimental alloy compositions from Bethlehem Steel Corporation were tested and compared to MIL-A-12560 specifications and to rolled homogeneous armor (RHA). These experimental alloys were controlled rolled on a laboratory mill with a finish temperature of 1600 F. Since the plates from this small mill are warped, the plates were flattened in a press using heated dies and subsequently quenched from a temperature greater than 1500 F. The plates were water quenched at the rate of 58 F/sec to room temperature. Regular mill practice is expected to have a finish temperature of 1500 F and the plate would be quenched from this temperature.

Lower carbon contents of steels for armored vehicles are being studied as a means of eliminating and/or minimizing welding preheat requirements during vehicle fabrication. And, AC/DQ processing is being studied as a means of achieving the strength levels required for armored vehicles at the lower carbon levels under consideration.

The AC/DQ processing is not currently being used by US steel mills but is used by Japanese and some European mills. If the AC/DQ processing is found to be advantageous, the technology will be transferred to US steel mills.

PROCEDURE

The heat analyses of the two experimental compositions, provided by Bethlehem Steel Corporation, BSC, were compared to typical 1-inch RHA. Through-thickness hardness obtained by BSC was compared to that for 1-inch RHA.

The V_{50} of the plates was measured against a .50 caliber armor piercing (AP) threat at 0-degree obliquity at the Materials Technology Laboratory (MTL) and compared to the MIL-A-12560 specification and to typical 1-inch RHA. Photomicrographs of the grain structure were obtained.

RESULTS AND DISCUSSION

The compositions of the two experimental alloys are compared to typical 1-inch RHA in Table 1. The carbon and manganese contents are lower than RHA and the experimental alloys contain either vanadium or columbium as well.

Table 1. CHEMICAL COMPOSITION, WEIGHT PERCENT, OF BSC STEELS VS. RHA

Element	BSC Alloy A	BSC Alloy B	RHA
C	0.16	0.17	0.25
Mn	1.09	1.07	1.59
P	0.006	0.006	0.020
S	0.004	0.004	0.004
Si	0.33	0.33	0.26
Mo	0.50	0.50	0.53
Cb	0.026	—	—
V	—	0.086	—
Al	0.033	0.039	NA
Ti	0.030	0.027	NA
B	0.002	0.001	0.0019
N	0.0063	0.0081	NA

The surface hardness of both sample steels was at the low end of that specified by MIL-A-12560. The through-thickness hardness, provided by BSC, is shown in Figure 1. In Alloy A, the columbium containing composition, the hardness varied an average of 2 HRC points. In Alloy B, the vanadium containing composition, the hardness varied slightly more, about 3 HRC points. Typically, the hardness of 1-inch RHA varies 1 to 2 points through the thickness.

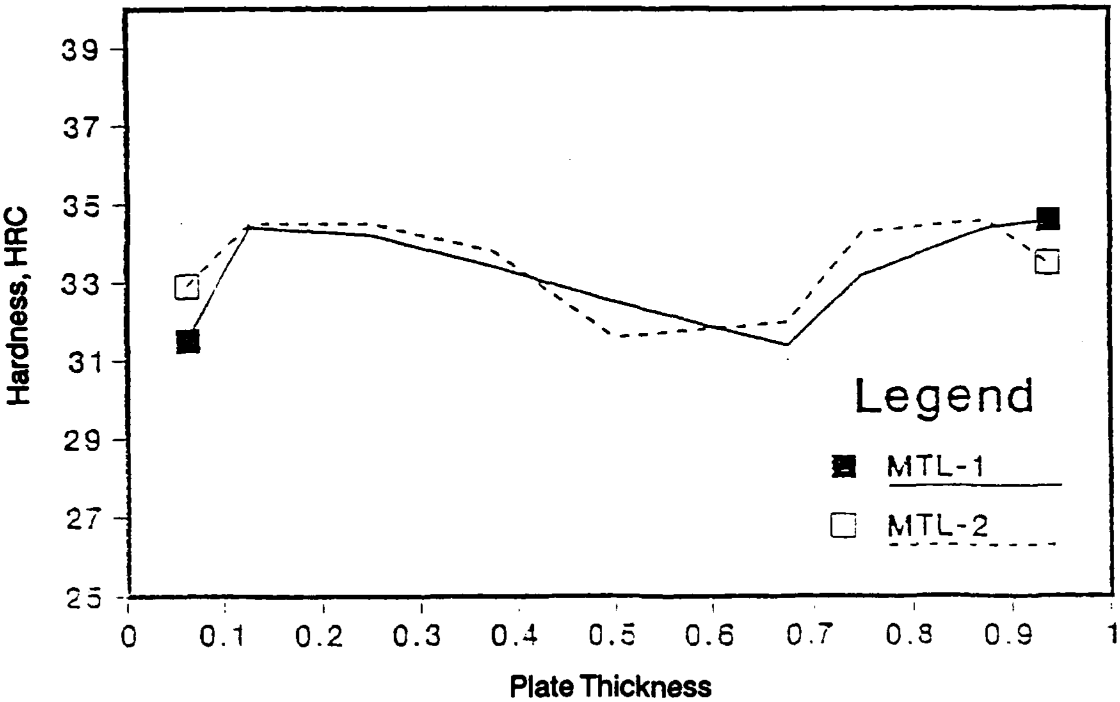
Charpy V-notch absorbed energy values supplied by BSC for the two compositions are shown in Table 2, compared to 1-inch RHA. The absorbed energy for the Cb-containing alloy (33 HRC) is at the high end of the range reported for RHA and the absorbed energy for the V-containing alloy (34 HRC) is greater than the high value of the range reported for RHA.

Table 2. TOUGHNESS OF 1-INCH LOW-C Mn-Mo-B-TYPE STEELS FROM BSC VS. RHA

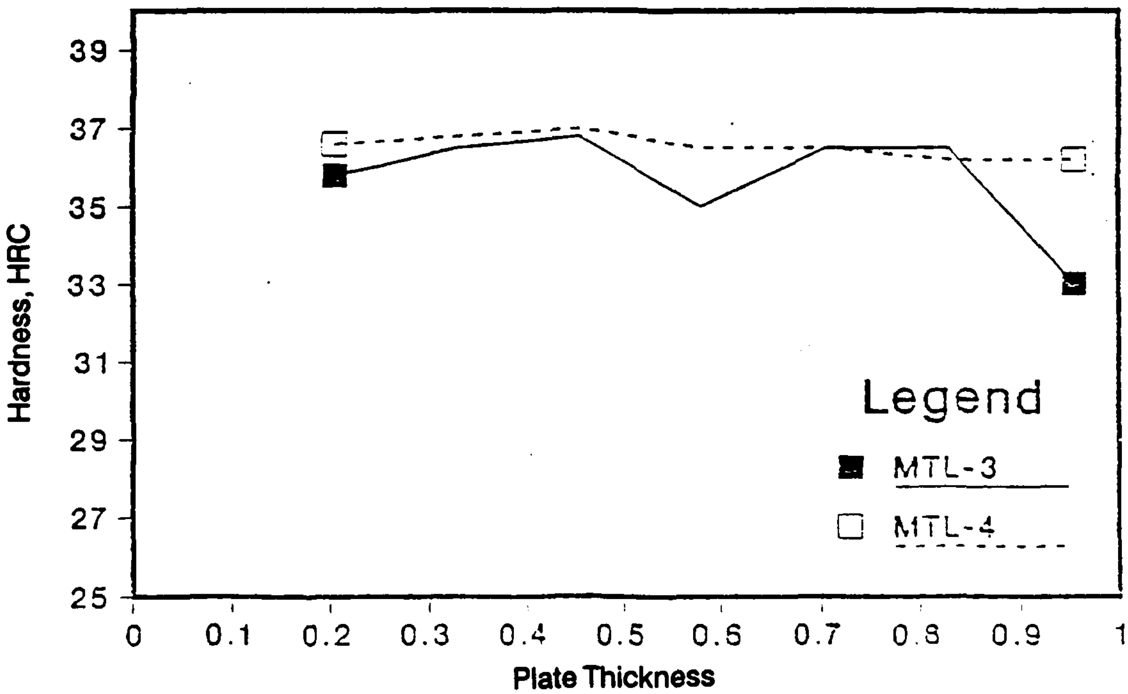
Source	CVN, -40 F ft.-lb
BSC, Alloy A (Mn-Mo-B-Cb)	28
BSC, Alloy B (Mn-Mo-B-V)	34
RHA	18-31
MIL-A-12560*	23.5 minimum

*At HRC 33.4

The measured V_{50} for the BSC alloys is shown in Table 3. The BSC experimental alloys had low measured V_{50} (and low hardness) for the thickness compared to the minimum specified by MIL-A-12560. Typically, RHA exceeds the minimum specified V_{50} by an average of 87 fps.



(a)



(b)

Figure 1. Through-thickness hardness of the BSC steels. (a) Alloy A, Mn-Mo-B-Cb composition, 2 plates, 1 heat. (b) Alloy B, Mn-Mo-B-V composition, 2 plates, 1 heat.

Table 3. BALLISTIC PERFORMANCE OF BSC EXPERIMENTAL ALLOYS FOR .50 CALIBER AP THREAT

Material		BHN	Ave. t inches	V_{50} fps	Minimum Specified*
Alloy A	1	327#	1.050	2732	2754
	2	330	1.039	2713	2738
Alloy B	3	340	1.038	2743	2736
	4	340	1.038	2743	2736

*MIL-A-12560
#Specified hardness range is 321 - 375. Note: RHA V_{50} exceeds the minimum specified by an average of 87 fps

Photomicrographs of the two experimental steels are shown in Figures 2 and 3. Both alloys show a typical rolling texture through the thickness but the Cb-containing alloy is better developed.

CONCLUSIONS

Two low-C direct ᵒⁿ ˋ.ᵢed (AC/DQ) alloys from Bethlehem Steel Corporation were evaluated as part of a ᵍᵉᵢ study of low-C AC/DQ steels for use as armor materials.

1. The alloys were similar to Mn-Mo-B RHA except for alloying additions of Cb or V, slightly lower Mn content, and the low-C content.

2. The surface hardness just met the minimum specified by MIL-A-12560. The through-thickness hardness of the experimental plate containing V varied slightly more than is typical of RHA. The Cb-containing plate variation was similar to that of RHA.

3. Toughness, as measured with the standard Charpy V-notch test, was well above the minimum specified for both of the compositions. The toughness of the alloy containing columbium was at the high end of the normal range of values found for RHA. The toughness of the alloy containing vanadium was greater than the typical range of values for RHA.

4. The two experimental steel compositions from BSC performed poorly in ballistic testing against a .50 caliber AP threat when compared to the minimum specified by MIL-A-12560 or to typical RHA.

ACKNOWLEDGMENT

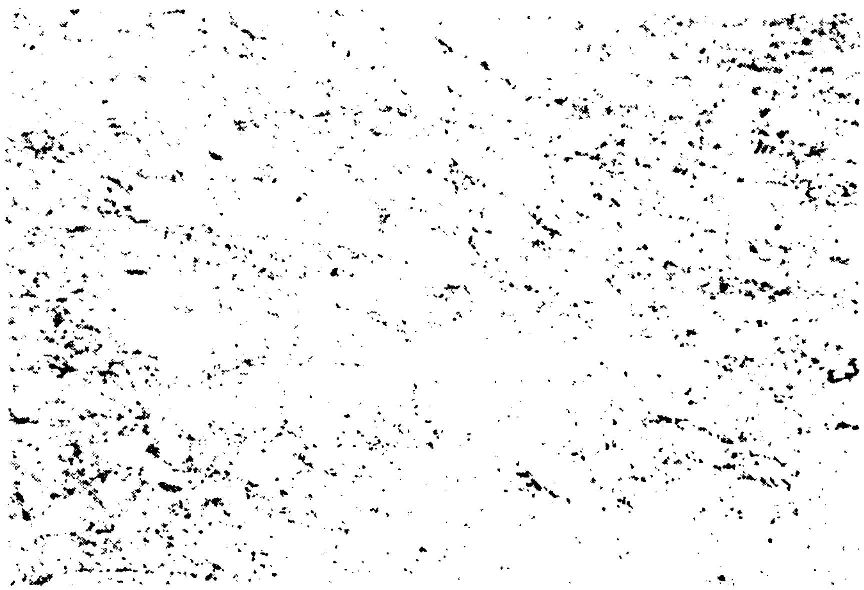
The author wishes to thank Mr. Arthur Ayvazian for sharing his vast knowledge of the properties of Rolled Homogeneous Armor steel.

(a)

(b)

Figure 2. Photomicrographs of the BSC experimental composition containing columbium, Alloy A. (a) 1/8 inch from edge. (b) 1/2 inch from edge. 500X.

(a)



(b)

Figure 3. Photomicrographs of the BSC experimental composition containing vanadium, Alloy B. (a) 1/8 inch from edge. (b) 1/2 inch from edge. 500X.

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1	Author

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
A SUMMARY OF STUDIES PERFORMED ON EXPERIMENTAL ACCELERATED COOLED/DIRECT QUENCHED PLATE STEELS FOR ARMOR APPLICATIONS AS PART OF THE TITLE III PROGRAM OF THE DEFENSE PRODUCTION ACT - Judith L. Bhansali

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Heat treatment

Technical Report MTL TR 89-105, December 1989, 30 pp-illus-tables

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